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Walter Judd

Notes for telegraphists.

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NOTES FOR TELEGRAPHISTS,

BY

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These notes make no pretence to originality, but it is hoped that they may be found useful to some of the daily increasing number who make Telegraphy their profession.

Those who wish to gain a further knowledge of this most interesting branch of applied science are strongly recommended to obtain Mr. Latimer Clark's invaluable little work, "Electrical Measurement."

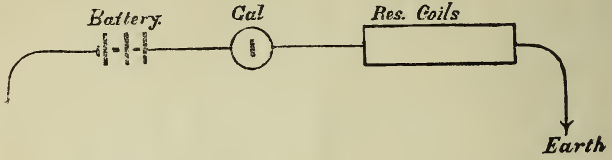
The assistance given by Mr. J. C. Cuff is cordially acknowledged.

For the sake of simplicity we will take Latimer Clark's definition of Electricity, viz.:—

> "A substance like water or gas, having a veritable existence, "and although easily convertible into heat, in other respects indes-"tructible."
>
> "To regard the earth as a vast reservoir, highly charged with "one kind of Electricity (positive), and regard a telegraph or a "Battery as an arrangement by which Electricity is pumped out of "the earth at one point and poured into it at another."

The first general principle is that *the quantity of Electricity, with a given Battery, which flows through an Electrical circuit, is strictly proportional inversely to the Resistance in that circuit.*

For instance, take your Battery, Galvanometer and Resistance Coils, and join them up as in the subjoined diagram :—



Unplug say 1,000 units or ohms (so called from Ohm, who first ascertained the laws of Electrical Resistance), then press your key down and note deflection, say 50 divisions; now unplug another 1,000 units, making 2,000 in all. Your deflection will then be 25 divisions, if your Galvanometer is such that its deflection is proportional to the amount of current passing.

In this example the resistance of Battery and Galvanometer is not taken into account, for the sake of simplicity; but as there is always a certain resistance both in Battery and Galvanometer, the foregoing example would not, in practice, be correct. Suppose our Battery to consist of 10 cells, giving a resistance of 200 ohms. The resistance of Galvanometer we will call 100 ohms. Now, if we unplug 1,000 ohms in resistance box, the total resistance in circuit will be—

Resistance	Box - - - - -	1,000
,,	Battery - - - -	200
,,	Galvanometer - - -	100
	Total - - -	1,300

With this total resistance we obtain our deflection of say 50 divisions. To reduce this to one-half we must unplug a further resistance of 1,300 ohms in the box, that is to say, we must double the resistance in circuit. The deflection is now reduced to one-half, that is to say, as the deflection on the Galvanometer merely indicates the amount of current passing, that the current is halved. It is, however, only with the mirror Galvanometer that the deflection is strictly proportional to the amount of current passing, because such a slight movement of the mirror is necessary to cause the light to travel a great distance.

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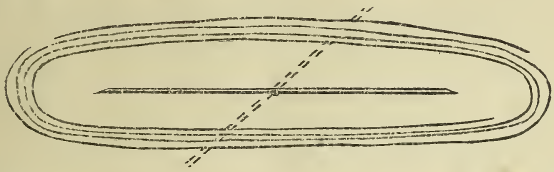
In an ordinary horizontal Galvanometer, when the needle is at rest, it is in the position shewn in the following diagram, that is, parallel to the coils; but when a current is passing through the wire, the needle is deflected, tending to place itself at right angles to the coil, as shewn by the dotted line. Now, in the first position, the current has its greatest power, but as the needle places itself at an angle with the coil, the effect of the current becomes weaker and weaker as the angle becomes larger, until when the needle is at right angles to the coil, the effect is nil, except to hold it in that position. So, supposing one cell will deflect the needle of a horizontal Galvanometer 30 divisions, two cells will not deflect it 60 divisions, for more power is required to move the needle over the second 30 than is required for the first, for the reasons given above. The needle of a Galvanometer, being a magnet, always points North and South, when at rest. It will sometimes happen that the coils are not in the same line with the needle, and, consequently, as in that case the needle makes an angle with the coils, the instrument is rendered less sensitive, the full effect of the current not being felt. Care should always be taken to avoid this. The mirror of a mirror Galvanometer should always look in the same direction as the face of the Galvanometer.



Our first rule, that the quantity of Electricity which with a given battery flows through a given circuit is inversely proportional to the resistance in that circuit, is generally expressed as under:—

$Q = \frac{E}{R}$; Q being written as the quotient of $\frac{E}{R}$.

Q is Quantity; E, Electromotive Force; R, Resistance. If $\frac{E}{R} = Q$, it is obvious that $\frac{E}{2R} = \frac{1}{2}Q$, and $\frac{E}{\frac{1}{2}R} = 2Q$, and so on.

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In testing an insulated line the resistance which the Dielectric, or insulating material, offers to the current is measured. No material has yet been found which will insulate perfectly, or, in other words, offer an infinite resistance to the passage of the electric current; so that in every mile of telegraph line there is a certain leakage, and if a line is in exactly the same condition throughout its length, there will be the same amount of leakage in each mile of its length—the same proportion of the charge in each finding its way to earth through the Dielectric. In two miles of line the leakage is double that in one mile. Conversely the leakage in one mile of line is half that in two miles; therefore, knowing that the amount of current flowing through any circuit is inversely proportional to its resistance, using the same battery power, it is clear that the insulation resistance of the one mile length is double that of the two mile length. Therefore we always *multiply* the observed resistance of an insulated line of telegraph by the number of knots it contains, to ascertain the resistance per knot.

When, however, testing the resistance of the *conductor*, the distant end is put to earth, and as in a good line the resistance of the dielectric is practically infinite, as compared with that of the conductor, we only concern ourselves with the latter. It is obvious that if a current has to pass through 2 miles of wire, it has to overcome double the resistance of 1 mile. A line of 1 mile in length only offers $\frac{1}{10}$ the resistance that is offered by 10 miles of similar wire, therefore we always *divide* the observed resistance of a line of telegraph, which is to earth at the distant end, by the number of knots it contains, to find the resistance per knot.

We now come to the second great principle, that *the quantity of electricity that flows through a circuit of given resistance is directly proportional to the electromotive force.*

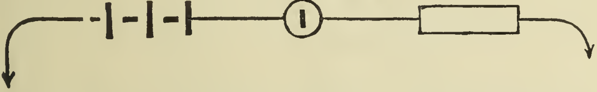
This is again

$$Q = \frac{E}{R}$$

Therefore $\frac{2\,E}{R} = 2\,Q$

and $\frac{\frac{1}{2}E}{R} = \frac{1}{2}\,Q$ and so on.

That is to say, if you double the Electromotive force or battery, the current is doubled, and if you halve it the current is halved. Here again we have to apply a correction. As the battery is increased or decreased, so the total resistance in circuit is increased or decreased. But the rule requires that the resistance should be *constant*, so that when the internal resistance of the battery is altered by increasing or reducing the number of cells, the resistance exterior to the battery must be changed, in order to keep the total resistance the same.



In the above diagram suppose the Battery, Galvanometer, and Resistance coils give respectively 200, 100, and 1,000 ohms resistance, making a total of 1,300, and through this circuit we get a certain current of electricity. If we halve the Battery we reduce its resistance to 100 ohms, and make the total resistance of the circuit 1,200 ohms, we must add 100 ohms so as to keep the resistance constant. Similarly, if we increase the battery and thereby increase the total resistance, we must deduct from the circuit an amount equal to that by which we have increased the B R, then, and only then shall we have a current proportional to the Electromotive force. In a circuit in which the resistance exterior to the battery is very small, the batteries should be so constructed as to give very small internal resistance. Take a circuit consisting of 10 cells giving 100 ohms, and a galvanometer giving 10 ohms resistance. Total resistance in circuit = 110 ohms.

The amount of current passing is expressed by $Q = \frac{E}{R}$. Now double the Battery or Electromotive force. By doing so you add another 100 ohms of resistance to the circuit. In the first instance the amount of current $Q = \frac{10}{110}$; in the second case $Q = \frac{20}{210} = \frac{10}{105}$, so the increase is only as $\frac{10}{105}$ is to $\frac{10}{110}$, the difference being very slight; the resistance added by each cell almost neutralizing its Electromotive force. The Batteries used for the Electromagnets of Sir William Thomson's Siphon Recorder, are constructed to give only $\frac{1}{10}$ of an ohm resistance for each cell, the external resistance of the circuit being only about 16 ohms. A cell with large plates gives less resistance than one with small plates. Several similar cells joined up in parallel arc, or Z to Z and C to C, form simply one cell with large plates, and the reciprocal of their number gives the resistance of the whole in terms of one cell. Thus 10 cells joined up in this way give a resistance equal to $\frac{1}{10}$ of the resistance of one of them taken singly.

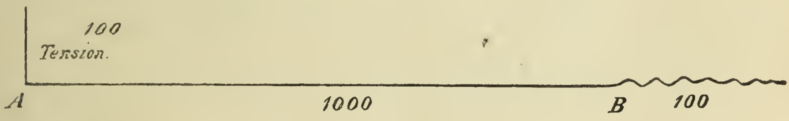
Tension or Potential is often confounded with Electromotive force; this is quite erroneous. Tension is the *result* of Electromotive force. On a telegraph line the Electromotive force remains constant, but the tension varies in every part of the line. Tension is not the quantity of electricity, but the intensity, the energy, so to speak. Lightning is an extreme case of tension, where the quantity is very minute. The tension of the Earth is for practical purposes taken at zero, and the + pole of a battery has a higher, and the — pole a lower tension than that of the earth. Put both poles of a battery to earth. A current immediately flows from the + pole to earth, while a current of exactly equal strength flows from the earth to the — pole of the battery. When the + pole of a battery is put to a cable, the other being to earth, the + current runs through the cable to earth at the distant end. When the — pole, however, is put to the cable and + to earth, the current flows from the earth into the cable at the distant end, and comes along the cable to the — pole of the battery, the tension of the earth being above that of the — pole, and a current always flows from the higher tension to the lower. The different effect of the two currents upon a Galvanometer may be explained in this way. They enter the coil in opposite directions, and therefore produce opposite effects.

In a circuit of uniform resistance the tension varies as the distance from the distant (or zero) end of the line (Latimer Clark.)

Take a point 10 miles distant from the distant end, and say the tension at that point is equal to $\frac{1}{10}$ of the tension at the point where the battery is applied to line. At a point 10 miles nearer the battery, we shall find the tention to be $\frac{2}{10}$. That is having doubled the distance from the distant end, we find double the amount of tension. Therefore at $\frac{1}{2}$ and $\frac{9}{10}$ of the distance from the distant end, we shall find the tension $\frac{1}{2}$ and $\frac{9}{10}$ respectively of the tension at the point where the battery is applied. It is important to thoroughly understand this.

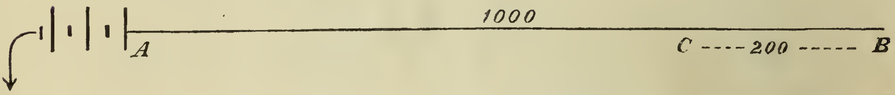
The amount of current flowing between two points is directly proportional to the difference of tension between those points.

We know how important a good "Earth" is in working. One great reason for that is, that the Earth being zero, we get as great a difference as possible between the end to which we apply the battery and the distant end; therefore the amount of current passing is as great as possible. If the "Earth" offers a high resistance, it has the same effect as if the circuit were lengthened, and the end of the "Line" is not at a zero tension, but something above it, proportionately to the resistance of the "Earth"; therefore the difference between the two ends being lessened, the amount of current passing is also lessened.



In the line A B the resistance of the conductor is a thousand ohms, and when B makes "good Earth" it is at zero. The tension at A is 100. If the "Earth" at B gives a resistance of 100 ohms, the resistance of the circuit will be 1,100 ohms. The tension at A being 100, what will it be at B, a point 100 ohms distant from the end of the circuit? B is $\frac{1}{11}$ of the resistance from the zero end, therefore the tension there is $\frac{1}{11}$ of the tension at A, $\frac{1}{11}$ of 100 = 9 nearly, instead of 0; consequently we get 10°/o less current.

The tension at the point where the battery is applied to the line does not equal the Electromotive force, but is always something less, for the battery forming part of the circuit the tension falls in it proportionately to its resistance. Hitherto, when finding the tension at any point in a line, the tension of the point of junction of battery and line has been taken as known. It will now be seen how the tension at any point can be determined from the Electromotive force.



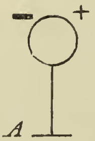
To the line A B of 1,000 ohms, apply a battery of 10 cells, giving 100 ohms resistance. Find the tension at a point C, 200 ohms distant from B. The resistance in circuit is 1,100 ohms. C is $\frac{2}{11}$ of this from B; therefore the tension at C is $\frac{2}{11}$ of 10 cells (the Electromotive force) = 1·82 nearly. Following is the formula given for this calculation by Latimer Clark in his "Electrical Measurement":—

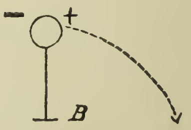
> "As the whole resistance of line and battery is to the resistance "measured from the distant end of the line, so is the Electromotive "force to the tension at the spot required."

In the preceding example, as 1,100 : 200 : : 10 : 1·82.

A knowledge of the phenomena of Induction is indispensable to every telegraphist, and a brief exposition of them here may be found useful.

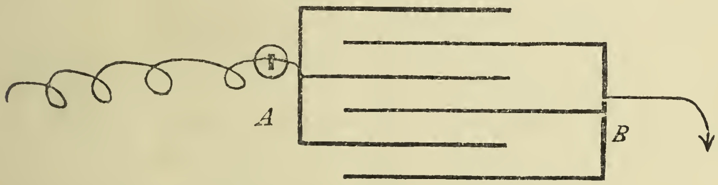
Take two insulated globes, A and B;





Charge A with, say, positive electricity. This charge will immediately disturb the distribution in B, which was normal before, and will repel the electricity of B to the other side (in the same way that similar poles of magnets repel one another) thereby leaving the near side minus.

The absence of electricity on the near side of B in its turn reacts on A, attracting its electricity, and this kind of seesaw goes on until a limit is reached, If B be now joined to earth the action is very much stimulated, for the electricity repelled by A runs away to the earth, and the reciprocal attraction and repulsion again goes on until the sum of the unequal amounts of electricity condensed on the adjacent sides of A and B is about equal to their normal amount. This is exactly the principle of the "Condensers" used in working a telegraph line. They are indispensable in working long cables; and it is well that their principle should be understood.



The above diagram represents a Condenser.

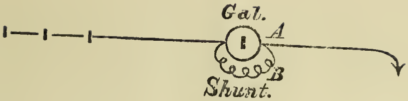
It consists of two sets of plates, separated from each other by some insulating material. The line is connected to one set and the earth to the other. Here we have again our two insulated bodies; the line plates representing A, and the earth plates B. A is charged with electricity from the line, and, acting on B, repels an exactly equal quantity of the like sign to earth.

The line conveys electricity just as a pipe conveys water, and the condenser acts as a reservoir. Place a Galvanometer, say, between the line and the condenser, and charge or fill up the condenser with electricity from the line. The current flows through the Galvanometer into the condenser until it is fully charged, deflecting the Galvanometer as it passes. The condenser charged, the flow ceases, and the Galvanometer is no longer deflected. The electricity in A must however get to earth in some way, and as A is insulated, its only passage is along the line to earth at the sending key. To do this it has again to flow through the Galvanometer, but in an *opposite* direction, reversing the deflection and helping the needle back to zero. The use of condensers also obviates the inconvenience caused by earth currents, for if the line is joined to condensers at each end, the cable is entirely insulated, and the earth currents can only affect the cable when they sufficiently and suddenly *vary* in strength or direction, and it is seldom that this is the case. It is quite immaterial whether the Galvanometer, or whatever instrument is used on a cable, be placed between the condenser and line or between the condenser and earth, as the amount of electricity leaving the condenser is precisely the same as that entering it, providing always that the insulation is perfect. In the case where the instrument is between the condenser and the earth, A being charged, an equal quantity of electricity leaves B and deflects the Galvanometer. On A being discharged, the disturbing influence on B is removed, and the electricity expelled from it returns; reunites with that which was attracted by A; the equilibrium of the body B is restored, and the electricity again becomes latent until again disturbed and excited by A being charged or electrified.

A cable is precisely the same as a condenser; the conductor taking the place of the body A, the earth taking the place of the body B, and the gutta percha or india-rubber that of the insulating material between them. A length of cable, having its farther end insulated, and a condenser of equal capacity, would give equal and similar results.

The retardation of current in long lines may be explained thus: The conductor representing A and the earth B; if A is charged, the electricity in B is excited; the two electricities attract each other and strive to unite. The current in A is, so to speak, held by the electricity in B, and retarded.

It is frequently found convenient, in practice, to "shunt" a Galvanometer or instrument, so that only a certain desired portion of the current may pass through it. This is done by providing another path for the current, which divides itself between the two circuits in inverse proportion to their resistances.



Let A be a Galvanometer shunted by the coil B, giving resistances respectively of 4654 and 60 units. As the current is inversely proportional to the resistance, it is evident that 4654 parts of the current will pass through the shunt and 60 parts through the Galvanometer. If the whole of the current $= 4654 + 60 = 4714$ parts, went through the Galvanometer, the effect would obviously be as many times greater as 4714 is greater than 60. $\frac{4714}{60} = 78{\cdot}5$ nearly, therefore in this case the deflection observed on the shunted Galvanometer would be multiplied by 78·5 to give the effect when the whole current is acting on it. This rule, formulated, is expressed thus: $\frac{G + S}{S} =$ multiplying power of the shunt.

Sometimes we wish to prepare a shunt having a certain ratio or multiplying power, which we will call n.

As above, $\frac{G + S}{S} = \frac{G}{S} + 1 = n,$

and $\frac{G}{S} = n - 1$

therefore $S = \frac{G}{n - 1}.$

Suppose we wish to use with a Galvanometer of 4645 ohms a shunt whose multiplying powers will be 10. The Resistance of Shunt required $= \frac{4654}{10-1} = \frac{4654}{9} = 517$ nearly.

It is often necessary to obtain the combined resistance of two circuits. The formula for this is, *divide the product of the two resistances by their sum.* For instance, to find the combined resistance of a Galvanometer and its shunt of 4654 and 60 ohms resistance respectively. $\frac{G \times S}{G + S} = \frac{4654 \times 60}{4654 + 60} = \frac{279240}{4714} = 59{\cdot}6.$ In cases where the shunt is small compared with the Galvanometer, the combined resistance may be safely taken as being the same as the shunt, unless extreme accuracy is required.

Following is the explanation of the formula :—

> "The *conducting power* of any circuits, whether simple or com-"bined, is of course inversely as their resistances; that is, it varies as "the reciprocals of their resistances." (Latimer Clark's Electrical Measurement.)

Conduction being the reciprocal of resistance, the conduction of G and S will be $\frac{1}{G} + \frac{1}{S}$. Bring to a common denominator and perform the operation of addition $=$ $\frac{G + S}{GS}$. The resistance is the reciprocal of this $= \frac{1}{\frac{G+S}{GS}} = \frac{GS}{G + S} = \frac{G \times S}{G + S}$.

We will now apply these principles to the explanation of the two principal tests used on Telegraph lines. Insulation test by deflection, and the test by Wheatstone's "Bridge."

The former is most simple.

A current is sent through a certain resistance, say 100,000 ohms, which we will call R, and the deflection noted which we will call D. The current is then sent through the cable (insulated at the further end), and a second deflection is obtained, which we will call d. The amount of current being inversely as the resistances, as d : D : : R : Insulation resistance of the cable, which is multiplied by the number of knots in the cable to give the Insulation resistance per knot.

In the above case we have not taken into consideration the resistance of the Battery and Galvanometer, nor have we supposed shunts to be used. In practice R will consist of the Resistance Coils, the Battery resistance, and the combined resistance of Shunt and Galvanometer; d and D must be corrected by applying the multiplying ratio of the shunts used in obtaining them. The above statement would then stand thus :—

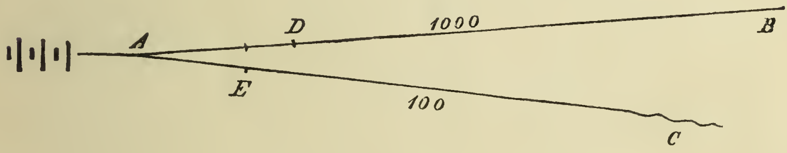
As $d \times \frac{G + S}{S} : D\,\frac{G + S}{S} : : (R + B + \frac{G \times S}{G + S}) :$ Insulation resistance of line.

The formula is usually expressed as below :—

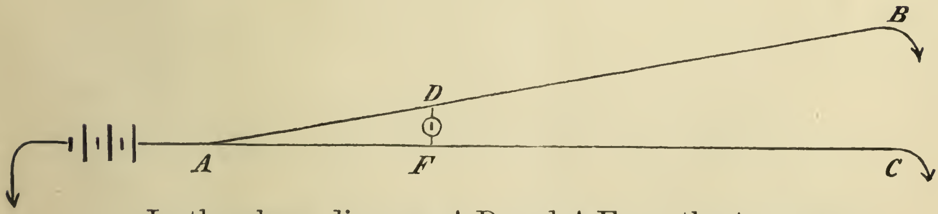
$$\frac{D \times \frac{G+S}{S} \times \left(R + B + \frac{G\,S}{G+S}\right)}{d \times \frac{G+S}{S}} \times \text{length of line} = \text{Insulation per knot.}$$

The Bridge test.

We have already learnt that in a circuit of uniform resistance the tension varies as the distance from the distant end of the line (Latimer Clark); therefore the tension varies *inversely* as the distance from the near end of the line.



The two circuits, A B, A C, have a resistance respectively of 1,000 and 100 units, and have a common tension at A. At a point D, $\frac{1}{10}$ of A B from A, the tension will equal $\frac{9}{10}$ of the tension at A. Also the tension at a point E, $\frac{1}{10}$ of A C from A, will equal $\frac{9}{10}$ of the tension at A. Therefore the tensions at D and E are equal. But A D = 100 ohms, and A E 10 ohms; therefore the tension in A B has fallen more slowly than in A C, and that in proportion to their lengths. If D and E were joined together no current would pass, as no current is possible between two points of equal tension.



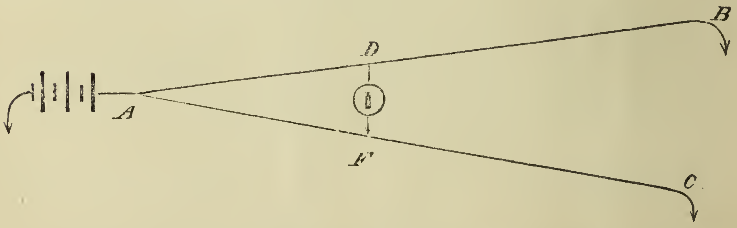
In the above diagram A D and A F are the two arms of a Wheatstone's bridge; F C the resistance coils, and

D B the line or resistance to be measured. If the resistance D B is within the compass of F C, A D and A F are made equal, and F C is varied until no current passes between D and F, the Galvanometer remaining at zero; D and F are then points of equal tension. Now A D and A F being equal, proves that the tension in the two circuits, A B and A C, falls equally in each; therefore the resistances of A B and A C are equal. From these take away the equal parts, A D, A F, then the remainders, D B and F C, are equal.

If F C is too small to measure D B, A D is made greater than A F generally, for convenience' sake, in the proportion of 10 or 100 to 1. F C is varied until the points D and F are of equal tension, and no current passes through the Galvanometer. A D being greater than A F proves that the tension in A B falls more slowly than in A C, in the proportion of A D to A F; therefore the resistance of the whole A B is greater than the resistance A C, in the proportion of A D to A F. Let A D = 10 A F; then the whole A B is equal to 10 A C, and the part A D being equal to 10 A F, the remainder, D B, equals 10 F C. This formulated is:—

As A F is to A D, so is F C to the resistance of the object measured.

Sir William Thomson's slides are used on precisely the same principle.



Although the slides are of 100,000 ohms resistance, yet we might call them 1,000 or 10,000, and our results would be just the same. For instance, if A F were 20,000 ohms, F C would be 80,000. We might call this 2 and 8, or 20 and 80 or 2,000 and 8,000. The *propor-*

tion of A F to F C would be unaltered. As a matter of fact the total resistance of a set of Thomson's slides is taken as 10,000, that being a convenient number; and a reading that really is 20,000 or 30,000, is read as 2,000 or 3,000.

A D is a fixed resistance, generally 10,000. D B is the resistance to be measured. A C is the slides, consisting of coils of wire giving a resistance of 100,000 ohms. As before, we desire to make the two points D and F of equal tension. The point F is moved on A C until this is the case, and no current flows through the Galvanometer. Then, as with the Bridge: As A F is to A D, so is F C to D B. We obtain the value of A F by inspection, there being a graduated scale affixed to the slides. It can be also expressed—

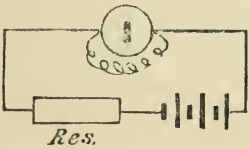
As A F : F C : : A D : D B.

To calculate a resistance from a Slide reading by common logarithms—

Call A F = D. F C = 10,000 − D. A D (10,000 ohms) = R, and D B = X.

$$\frac{D}{10{,}000-D}=\frac{R}{X}\quad X=R\,\frac{10{,}000-D}{D}=R\left(\frac{10{,}000}{D}-1\right)=\frac{R\,2}{D}-10{,}000=\frac{100{,}000{,}000}{D}-10{,}000=\text{nat.}\,(8-\log.\,D)-10{,}000.$$

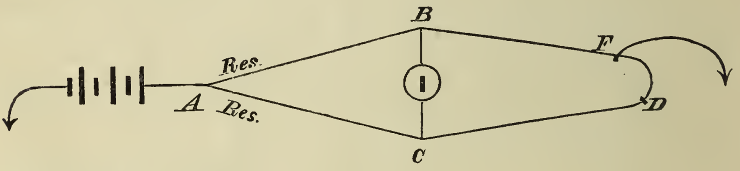
The test for measuring the resistance of a battery is often necessary, and is taken as under for a battery of high resistance:—



The battery is joined up in circuit with a box of resistance coils and a Galvanometer shunted with a short piece of fine wire. The resistance in the box is plugged out, and that of the shunted Galvanometer being extremely small, the only appreciable resistance in circuit is that of the battery itself. Note the deflection produced; then unplug resistance in the box until the deflection is reduced to one-half, thus showing that the resistance of the circuit has been doubled. Obviously the resistance unplugged in the box equals that of the battery.

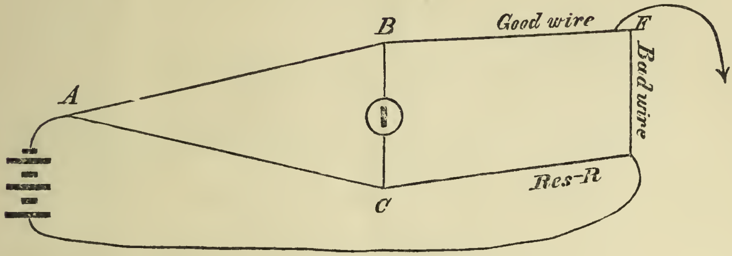
Some explanation of the tests used in localising faults in telegraph lines may be acceptable.

The simplest is the "loop test," when there is a good wire whose resistance is known, which can be looped with the faulty one at the distant end. The resistance of the latter, when perfect, should be obtained from previous records.



A B and A C are resistances used as the arms of a bridge, A B being made less than A C. B D and C D are respectively the bad and good wires looped together at D. F is the fault through which the current passes to earth, and which it is desired to localise. A B and A C are adjusted until no current passes between B and C. Then as A C : A B : : C F : B F. But B F and C F are both unknown. We know, however, the total resistance of the circuit B F C. Now if $\frac{AC}{AB} = \frac{CF}{BF}$, therefore $\frac{AC + AB}{AB} = \frac{CF + BF}{BF}$, that is, as the whole resistance of B A C is to the resistance of A B, so is the whole resistance of B F C to the resistance of B F.

If the resistances of the two wires are unknown, they can be obtained in the following manner, being looped as before:—



A B and A C are the arms of a Wheatstone's bridge. Adjust R. until no current passes between B and C. As A C : A B : : R to the resistance of the two wires. The fault at F does not interfere with the test, as it is the only earth connection in the circuit.

When, however, we have only a single line, some other method must be adopted. Blavier's formula is generally used.

Three resistances are required, viz. :—

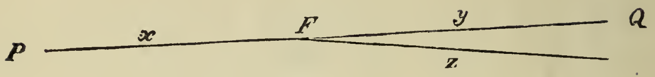
Resistance when line perfect = P
" " " free = F
" " " earthed = E

Subtract E from P and F. Multiply the two differences; extract the square root of their product, and finally subtract this result from E. This will give the distance of the fault from the testing station. Call this X.

Formula :—

$$X = E - \sqrt{(P - E)(F - E)}$$

Explanatian of Formula :—



Let P Q be a line with a fault at F.

Let $P =$ Resistance when perfect $= X + Y.$

$F =$ Resistance when free $= X + Z.$

$E =$ Resistance when earthed $= X + \frac{Y\,Z}{Y + Z}$

Therefore—

$$Y = P - X.$$

$$Z = F - X.$$

$$E = X + \frac{(P-X)\ (F-X)}{P-X + F-X}$$

$$= \frac{PX + FX - 2X^2 + FP - FX - PX + X^2}{P + F - 2X}$$

$$= \frac{FP - X^2}{P + F - 2X}$$

$$\therefore PE + EF - 2EX = FP - X^2$$

$$X^2 - 2EX = FP - PE - EF$$

$$X^2 - 2EX + E^2 = FP - PE - EF + E^2$$

$$X - E = \pm\sqrt{FP - PE - EF + E^2}$$

$$X = E - \sqrt{FP - PE - EF + E^2}$$

$$= E - \sqrt{(F-E)\ (P-E)}$$

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